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Radial growth of *Platycladus orientalis* Linn. and its growth resilience after extreme droughts along a precipitation gradient

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Abstract: Under current climate warming, the growth resilience of plantation forests after extreme droughts has garnered increasing attention. *Platycladus orientalis* Linn. is an evergreen tree species commonly used for afforestation, and the stability of *P. orientalis* plantation forests in the Loess Hilly region directly affects the ecological and environmental security of the entire Loess Plateau of China. However, systematic analyses of the growth resilience of *P. orientalis* plantation forests after extreme droughts along precipitation gradients remain scarce. In this study, we collected tree ring samples of *P. orientalis* along a precipitation gradient (255, 400, and 517 mm) from 2021 to 2023 and used dendroecological methods to explore the growth resilience of *P. orientalis* to drought stress on the Loess Plateau. Our findings revealed that the growth resilience of *P. orientalis* increased with increasing precipitation, enabling the trees to recover to the pre-drought growth levels. In regions with low precipitation (255 mm), the plantation forests were more sensitive to extreme droughts, struggling to recover to previous growth levels, necessitating conditional artificial irrigation. In regions with medium precipitation (400 mm), the growth of *P. orientalis* was significantly limited by drought stress and exhibited some recovery ability after extreme droughts, therefore warranting management through rainwater harvesting and conservation measures. Conversely, in regions with high precipitation (517 mm), the impacts of extreme droughts on *P. orientalis* plantation forests were relatively minor. This study underscored the need for targeted strategies tailored to different precipitation conditions rather than a "one-size-fits-all" approach to utilize precipitation resources effectively and maximize the ecological benefits of plantation forests. The findings will help maintain the stability of plantation forests and improve their ecosystem service functions in arid and semi-arid areas.

Keywords: *Platycladus orientalis*; tree ring; extreme drought; growth resilience; precipitation gradient; Loess Plateau

1 Introduction

Currently, droughts are increasing in frequency and intensity with global warming, leading to an

expansion of their impacts (IPCC, 2021; Jiang and Wang, 2021; Li et al., 2023). Extreme weather and climate events, particularly droughts, are current areas of focus in climate change research (Wang et al., 2022; Giana et al., 2023; Oggioni et al., 2024), posing new challenges for adaptation, management, and response to climate change (Dang et al., 2025).

On the Loess Plateau of China, severe soil erosion has negatively impacted the local ecological environment and human life (Yang et al., 2019; Fu et al., 2023; Su et al., 2024). Consequently, large-scale vegetation restoration projects have been implemented by the Chinese government (Zhong et al., 2021; Tian et al., 2022; Che et al., 2023a). The construction of plantation forests is crucial for windbreaks, sand fixation, carbon sequestration, and oxygen release on the Loess Plateau (Zhang et al., 2024). However, extreme droughts have jeopardized the success of these efforts. Extreme droughts severely limit the survival and growth of planted (or natural) trees (Jules et al., 2016; Earles et al., 2018; Wang et al., 2022). Furthermore, cascading disturbances, including forest fires and insect outbreaks, can lead to forest degradation or the death of individual trees, thereby affecting the stability of forest ecosystems (Allen et al., 2010; Xiao et al., 2020; Che et al., 2022).

Dendroecology can help establish long-term climate–growth relationships and provide a scientific basis for forest ecological management based on research results (Wang et al., 2021; Che et al., 2023a; Li et al., 2023). Studies have been conducted to analyze tree growth and drought stress from various aspects, including management practices, tree species, and stand structures. For example, research has shown that artificial irrigation helps alleviate the limitation of drought on the growth of plantation forests (Che et al., 2024), that different tree species have different suitable growth habitats (Navarro-Cerrilloa et al., 2020), and that mixed forests exhibit stronger recovery abilities than pure forests after extreme droughts (Feng et al., 2022). In China, dendroecological studies of plantation forests have mainly focused on the North-central China, North China, and Northeast China (Zhong et al., 2021; Li et al., 2023; Su et al., 2024), with a major focus on the growth resilience of different tree species after extreme droughts and the vulnerability of individual tree species to extreme droughts under different environmental conditions. These research efforts have concluded that different tree species and the same tree species in different habitats will exhibit different growth variations. However, relatively few studies have investigated the recovery ability of planted *Platycladus orientalis* Linn. (a tree species commonly used for afforestation) after extreme droughts along precipitation gradients.

P. orientalis belongs to the subphylum Gymnospermae of the family Cupressaceae and is an evergreen coniferous tree species that originated in China. It is among the most widely distributed coniferous tree species in China. Because of its high tolerance for barrenness and high adaptability, *P. orientalis* can grow normally on steep rock walls and slopes and requires minimal water. It has significant functions in water-soil conservation. Furthermore, it demonstrates robust adaptability to parent rock materials, allowing for the afforestation of various bedrocks and parent rock materials. Consequently, it has been introduced to the Loess Plateau region and has become a dominant tree species for afforestation (Jiang et al., 2015; Che et al., 2023b; Zhang et al., 2024). *P. orientalis* plantation forests cover almost all of China, with particular emphasis on the Loess Plateau, mainly found in the central and southeastern Gansu Province, central and southern Shaanxi Province, and central and northern Shanxi Province.

This study used dendroecological methods to systematically analyze the growth resilience of *P. orientalis* after extreme droughts across a precipitation gradient (255, 400, and 517 mm) on the Loess Plateau. Given that tree growth in arid areas is primarily limited by water availability, we hypothesized that *P. orientalis* in areas with higher precipitation might possess a greater recovery ability after extreme droughts than that in areas with relatively lower precipitation. Through this study, we sought to answer the following two questions: (1) does *P. orientalis* in regions with higher precipitation have a higher recovery ability than that in regions with lower precipitation? and (2) how can the findings on growth resilience be applied to guide the future management of plantation forests? Our study results will provide a novel perspective on forest ecological management with the ultimate goal of enhancing the stability of plantation forests and improving their ecosystem services.

2　Materials and methods

2.1　Study area

The sampling sites in this study are located on the western Loess Plateau, China (Fig. 1). Because of its inland location, where marine moisture cannot easily reach directly, combined with the blocking effect of the Qinghai-Xizang Plateau, a typical temperate continental semi-arid climate has formed on the Loess Plateau (Che et al., 2023a). The landform is predominantly characterized by gully-ridden loess hills. Six sampling sites were selected for this study and they were classified into three precipitation levels: "high" for the SCZ and TZS sites with an annual precipitation of 517 mm, "medium" for the CKZ and QLS sites with an annual precipitation of 400 mm, and "low" for the DWS and XJS sites with an annual precipitation of 255 mm. Samples from the low-precipitation regions (with an annual mean temperature of 7.24°C) were obtained in August 2023. Specifically, the DWS and XJS sites are located within the Education Department forest farm and Xujiashan National Forest Park in Lanzhou City of Gansu Province, respectively, where artificial irrigation is conducted for *P. orientalis*. Irrigation is scheduled 4 times a year and 130 mm each time. However, because of factors such as pipeline damage, irrigation actually takes place only one or two times a year, and the irrigation amount each time is typically less than 130 mm. Samples from the medium-precipitation regions (with an annual mean temperature of 7.14°C) were obtained in July 2021. Samples from the high-precipitation regions (with an annual mean temperature of 11.28°C) were obtained in July 2021. Notably, the SCZ site represents a natural forest, and this sampling site was selected mainly for comparative analysis of the growth resilience of *P. orientali* after extreme droughts under the same precipitation conditions. Detailed information about each sampling site is presented in Table 1.

2.2　Tree ring and meteorological data

Tree core samples of *P. orientalis* were obtained following international dendrochronological sampling standards (Sun et al., 2021). The sample sizes for each sampling site are listed in Table 1. A 5.15 mm-diameter increment borer was used to obtain the tree cores, and the tree cores were packed in plastic tubes. Subsequently, the tree core samples were fixed, dried, and polished, and tree ring widths were measured using a LINTAB 6 system (Rinntech, Heidelberg, Germany) to
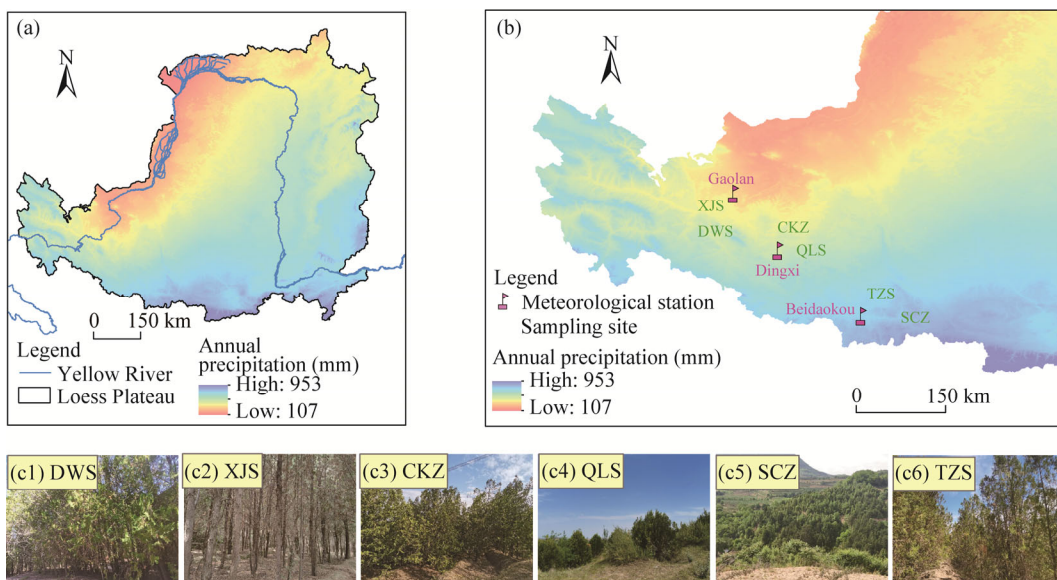
Fig. 1　Overview of the Loess Plateau (a) and distribution of the sampling sites and their nearest meteorological stations on the western Loess Plateau (b), as well as photographs showing the landscape of each sampling site (c1–c6)

Table 1   Detailed information and statistical parameters of residual chronologies at the sampling sites

Parameter	Sampling site					
	XJS	DWS	CKZ	QLS	SCZ	TZS
Latitude	36°05′24″N	36°01′48″N	35°43′48″N	35°38′24″N	34°31′48″N	34°33′36″N
Longitude	103°51′00″E	103°55′12″E	104°30′00″E	104°40′12″E	106°15′36″E	106°06′36″E
Elevation (m)	1669	1754	1995	2245	1151	1181
Slope direction	South	South	Northwest	South	South	Northwest
Chronology length	1986–2023	1981–2023	1967–2021	1980–2021	1972–2021	1955–2021
Sample size	40	51	37	39	31	38
MS	0.176	0.264	0.349	0.256	0.326	0.220
SNR	7.889	7.994	11.279	35.842	8.988	9.494
EPS	0.888	0.889	0.919	0.973	0.900	0.905
Inter-series correlation	0.450	0.456	0.521	0.648	0.475	0.431
Tree height (m)	8.4	5.7	8.5	4.5	8.2	7.9

Note: MS, mean sensitivity; SNR, signal to noise ratio; EPS, expressed population signal.

indicate tree growth. The cross-dating results were obtained using the COFECHA procedure (Holmes, 1983), and the regional curve standardization method was used for detrending (Che et al., 2023b). Considering that the method requires a large number of samples with consistent physiological age and that tree rings need to be measured in the pith, we used the residual chronology to analyze climate–growth relationships. The statistical parameters of the residual chronologies are listed in Table 1.

The monthly mean temperature and monthly precipitation data (1955–2023) used in this study are from China Meteorological Data Network (https://data.cma.cn). The selected meteorological stations are closest to the six sampling sites, namely, Gaolan (closest to the XJS and DWS sites), Dingxi (closest to the CKZ and QLS sites), and Beidaokou (closest to the SCZ and TZS sites).

This study assessed the relationships between tree growth and three climate variables: monthly mean temperature, monthly precipitation, and standardized precipitation evapotranspiration index (SPEI). Data on the first two climate variables were extracted from meteorological stations. Comparative analysis has shown that the SPEI at the 1-month time scale (SPEI_01) has more significant effects on trees in arid and semi-arid areas (Wang et al., 2020; Che et al., 2022). Hence, we chose the SPEI_01 to analyze the relationships between tree growth and drought stress (Wang et al., 2020). The SPEI_01 values were calculated using the meteorological data at meteorological stations (Vicente-Serrano et al., 2010). However, for the SCZ and TZS sites, no data on wind speed and sunshine duration were recorded at the meteorological station; thus, the SPEI_01 values for these sites were taken from the published time series of SPEI_01 data at 0.5°×0.5° resolution from the European Climate Assessment & Dataset provided by the Climatic Research Unit of the University of East Anglia (https://spei.csic.es/database.html).

2.3   Extreme drought years and growth resilience components

This study used the relative growth change method to identify extreme drought years at the sampling sites (Schweingruber et al., 1990; Wang et al., 2019). This method first calculates the ratio of the individual growth (R-t) of all trees in a given year (t) to the average growth (R-n) over the preceding number of years (n). When the result is below a certain threshold, target individual i is concluded to have experienced an abnormal decrease in growth in that year. If the number of individuals with abnormal growth reduction exceeds a certain proportion of the total sample, an abnormal growth reduction at the site level is concluded to have occurred in that year. In this study, the average SPEI_01 from March to September in extreme drought years was required to be less than zero to indicate a drought-induced decline in tree growth (Beguería et al., 2014). The SPEI_01 has been found to correspond well with actual water shortages, which was calculated

using the monthly average temperature and monthly precipitation data according to the method described by Beguería et al. (2014) (Fig. S1; Zang et al., 2020). This study concentrated on abnormal growth reduction events caused by extreme droughts, and the occurrence of an abnormal growth reduction event can be indicated by a threshold of 60.00% of the tree ring width series displaying a decline of at least 30.00% compared with the previous two years (Wang et al., 2019; Wang et al., 2022). It is important to note that all extreme drought years in this study were characterised by the same drought intensity ($-1 < SPEI\_01 < 0$) (Beguería et al., 2014). Therefore, this study mainly focused on analyzing the growth resilience of *P. orientalis* to extreme droughts across a precipitation gradient with the same drought intensity.

This study employed the indices of resistance (Rt), recovery (Rc), and resilience (Rs) to explore the relationship between tree growth and extreme drought (Lloret et al., 2011). However, these indices are limited in their ability to compare post-drought recovery abilities across different sites or stand structures. Given this limitation, this study employed the theory of the "Line of full resilience" introduced by Schwarz et al. (2020) to analyze the recovery ability of plantation forests after extreme droughts. This method initially postulates that a tree can fully recover after a defined drought event, that is, $Rs=1$, thereby establishing a "Line of full resilience" ($Rc=1/Rt$). Subsequently, the calculated Rt and Rc values were used to fit a "Line of actual resilience" ($Rc=\alpha Rt^{\beta}$, where α and β are the coefficient and the exponent of the power function, respectively) (Wang et al., 2022). Finally, a more systematic understanding of the relationship between tree growth and extreme drought can be obtained by comparing the intersection points of the two curves. For example, if the abscissa of the intersection point of the two curves is 0.4645, it means that this tree species has a probability of 53.55% to fully recover after extreme droughts. In other words, the closer the abscissa of the intersection point of the two curves is to zero, the stronger the ability of the trees is to fully recover after extreme droughts. Conversely, the closer the abscissa of the intersection point of the two curves is to 1.0000, the less likely the species is to recover (Schwarz et al., 2020).

2.4 Statistical analyses

In this study, climate–growth relationships were performed using Dendroclima v.2002 software. Comparisons of growth resilience indices among different sampling sites within the same extreme drought year were calculated using one-way analysis of variance (ANOVA) performed in the IBM SPSS Statistics v.25.0 software. Graphical presentations of the results were created using SigmaPlot v.15.0 software and Origin v.2024 software.

3 Results

3.1 Climate–growth relationships of *P. orientalis* along a precipitation gradient

Residual chronology analysis revealed that in the low-precipitation regions, the chronologies of *P. orientalis* spanned 1986–2023 at the XJS site and 1981–2023 at the DWS site (Fig. 2a). In the medium-precipitation regions, the chronologies of *P. orientalis* at CKZ and QLS sites spanned 1967–2021 and 1980–2021, respectively (Fig. 2b). Moreover, in the high-precipitation regions, the chronologies of *P. orientalis* at SCZ and TZS sites spanned 1972–2021 and 1955–2021, respectively (Fig. 2c). The residual chronologies along a precipitation gradient exhibited a consistent growth fluctuation phenomenon, indicating the limiting effect of water conditions on tree growth.

In the low-precipitation regions, the growth of *P. orientalis* at the XJS site with artificial irrigation was significantly positively correlated with temperature in March, May, and June ($P < 0.05$), whereas no significant correlations were observed at the DWS site (Fig. 3a). In the medium-precipitation regions, the growth of *P. orientalis* at CKZ and QLS sites did not exhibit a significant correlation with temperature throughout the year. In the high-precipitation regions, significant negative correlations between tree growth and temperature were observed in January at the SCZ site, in February at SCZ and TZS sites, and in September at the SCZ site.
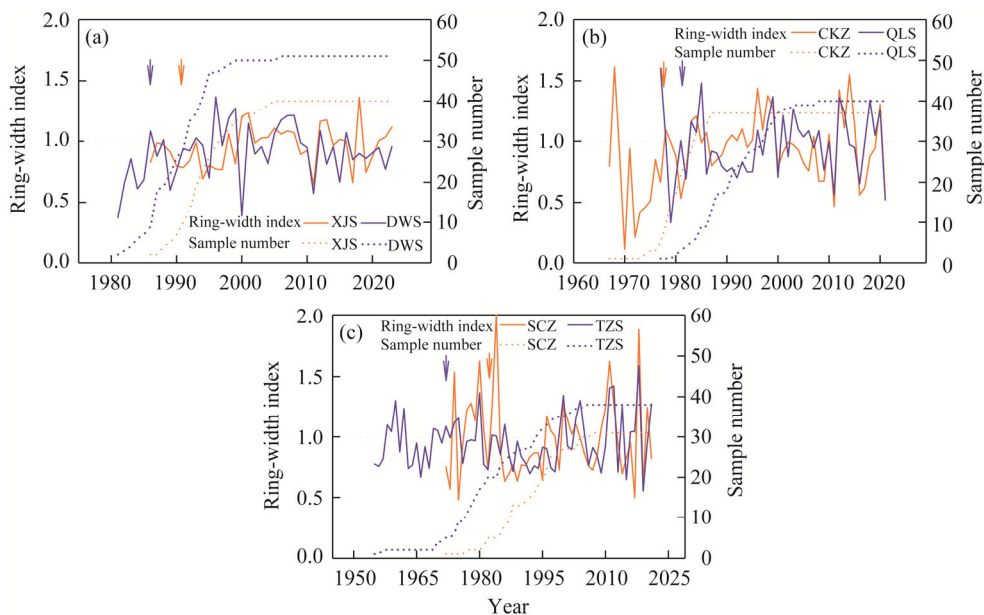
Fig. 2   Residual chronologies of *Platycladus orientalis* Linn. at six sampling sites across a precipitation gradient. (a), low precipitation level; (b), medium precipitation level; (c), high precipitation level. Data at the right side of the arrow had the subsample signal strength (SSS) values above 0.85.

In the low-precipitation regions, a significant positive correlation between tree growth and precipitation at XJS and DWS sites appeared in September and July, respectively (Fig. 3b). In the medium-precipitation regions, a significant positive correlation between tree growth and precipitation was observed in June at the CKZ site and in May at the QLS site. In the high-precipitation regions, a positive correlation between tree growth and precipitation was observed in September at the SCZ site and in January at SCZ and TZS sites.

In the low-precipitation regions, the growth of *P. orientalis* at the XJS site with artificial irrigation showed a significant negative correlation with SPEI_01 in March and a positive correlation in September (Fig. 3c). A significant positive correlation between tree growth and SPEI_01 was observed in July at the DWS site. In the medium-precipitation regions, significant positive correlations between tree growth and SPEI_01were observed in June at the CKZ site and in May at the QLS site. Moreover, in the high-precipitation regions, the growth of *P. orientalis* at the SCZ site was significantly negatively correlated with SPEI_01 in December of the previous year but significantly positively correlated with SPEI_01 in January. No significant correlations between tree growth and SPEI_01were observed at the TZS site.
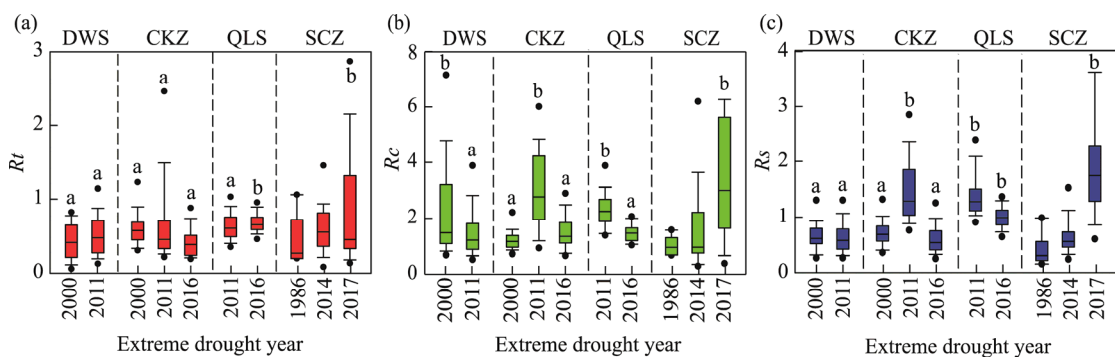
3.2   Growth resilience of *P. orientalis* after extreme droughts along a precipitation gradient

This study identified the following extreme droughts for each sampling site: 2000 and 2011 at the DWS site, 2000, 2011, and 2016 at the CKZ site, 2011 and 2016 at the QLS site, 1986, 2014, and 2017 at the SCZ site, and 1982, 2006, and 2015 at the TZS site. To facilitate comparison, we selected the extreme drought years 2000 (for DWS and CKZ sites), 2011 (for DWS, CKZ, and QLS sites), 2016 (for CKZ and QLS sites), and 2017 (for the SCZ site). In 2000 and 2011, there were no significant differences in the Rt of *P. orientalis* after extreme droughts at the sampling sites under different precipitation conditions (Fig. 4a). However, in 2016 and 2017, the Rt of *P. orientalis* was significantly higher at the SCZ site with high precipitation than at the CKZ site with medium precipitation ($P<0.05$).

P. orientalis at CKZ and QLS sites with medium precipitation showed significantly higher Rc after the extreme drought in 2011 than that at the DWS site with low precipitation ($P<0.05$; Fig. 4b). At the SCZ site with high precipitation, the Rc of *P. orientalis* after the extreme drought in
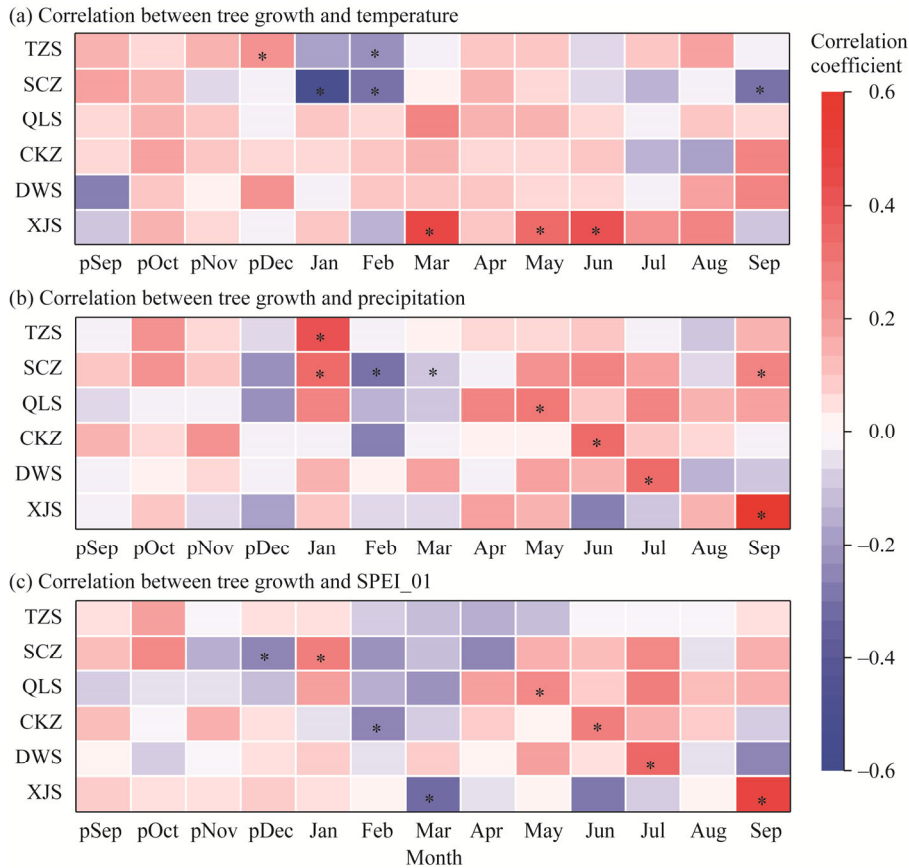
Fig. 3 Correlations between tree growth and temperature (a), tree growth and precipitation (b), and tree growth and SPEI_01 (c) at six sampling sites along a precipitation gradient. SPEI_01, standardized precipitation evapotranspiration index at the 1-month time scale. pSep, pOct, pNov, and pDec represent September, October, November, and December of the previous year, respectively. * indicates the significant correlation at $P<0.05$ level.

Fig. 4 Differences of Rt (a), Rc (b), and Rs (c) of *P. orientalis* after extreme droughts at different sampling sites along a precipitation gradient. Rt, Rc, and Rs are indices of resistance, recovery, and resilience, respectively. Different lowercase letters indicate significant differences among different sampling sites within the same extreme drought year at $P<0.05$ level. Note that the significance test was conducted for the extreme drought years 2016 and 2017 with the same drought intensity under different precipitation levels and no significance tests were conducted for the extreme drought years 1986 and 2014 at the SCZ site. The black dots indicate outliers, the box boundaries denote the 25th and 75th percentiles, and the line in the box denotes the median.

2017 was significantly higher than that at CKZ and QLS sites with medium precipitation.

When we compared the Rs of *P. orientalis* after the extreme drought in 2011, we found that at CKZ and QLS sites with medium precipitation, the Rs of *P. orientalis* was significantly higher

than that at the DWS site with low precipitation ($P<0.05$; Fig. 4c). We also found that the *Rs* of *P. orientalis* at the SCZ site with high precipitation was significantly higher than that at the CKZ site with medium precipitation.

3.3 Recovery ability of *P. orientalis* along a precipitation gradient

The results of the full resilience theory analysis showed that in the low-precipitation regions, there was no distinct intersection point between the two curves (Fig. 5a), indicating that the impacts of extreme droughts on tree growth in these regions were irreversible. As precipitation increased, the abscissa of the intersection point of the two curves for *P. orientalis* in the medium-precipitation regions was 0.5223, implying a possibility of 47.77% for *P. orientalis* to fully recover after extreme droughts (Fig. 5b). In the high-precipitation regions, the abscissa of the intersection point of the two curves was 0.6761, indicating a possibility of 32.39% for *P. orientalis* to fully recover after extreme droughts (Fig. 5c).
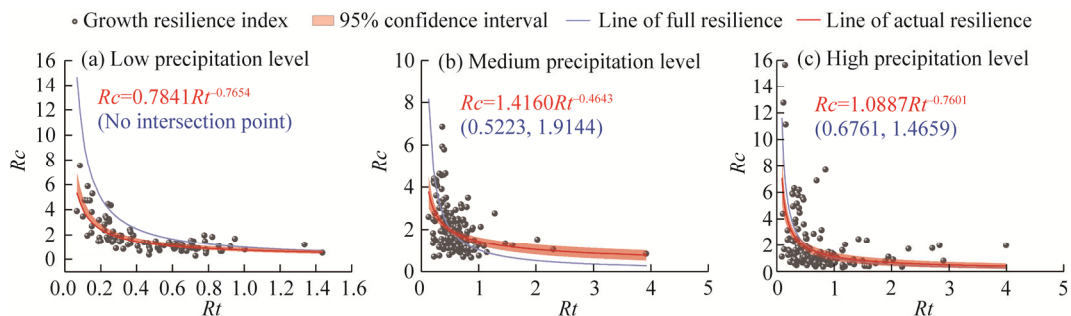
Fig. 5 Differences in the recovery ability of *P. orientalis* across a precipitation gradient. (a), low precipitation level; (b), medium precipitation level; (c), high precipitation level. The equation with red color is the fitted power function and numbers with blue color are the horizontal and vertical coordinates of the intersection point of the two curves in each figure.

4 Discussion

4.1 Enhanced growth resilience of *P. orientalis* after extreme droughts under high precipitation condition

The climate–growth relationship analysis showed that the growth of *P. orientalis* at the XJS site was positively correlated with temperature in March. During this period, high temperatures promote early germination of *P. orientalis*, thereby extending the growing season (Jiang et al., 2015; Che et al., 2023b; Zhang et al., 2024). Generally, in semi-arid areas, water availability is a major limitation for tree growth (Zhang et al., 2016; Fang et al., 2017; Wang et al., 2020). Tree growth at the XJS site with low precipitation was negatively correlated with SPEI_01 in March, mainly because of the artificial irrigation at this site during this period (Xiao et al., 2019). Tree growth is also limited by drought stress in September of the current year, although September is the end of the growing season (with an average monthly precipitation of only 35 mm) for *P. orientalis* (Che et al., 2023b). Precipitation during this period will remain in the soil, thereby replenishing the water required for the growth of trees in spring of the following year (Yang et al., 2023). However, scarce precipitation does not meet the normal growth requirements of trees. Therefore, the local government implemented artificial irrigation of the plantation forests in this area, thereby alleviating the limitations imposed by scarce precipitation on tree growth (Yang et al., 2023; Lu et al., 2024; Zhang et al., 2024). In the medium-precipitation regions, the growth of *P. orientalis* was limited by drought stress in May at the QLS site and in June at the CKZ site. It can be observed that there is good consistency between the relationships of tree growth with precipitation and SPEI_01. Excessively high temperatures can intensify plant transpiration and soil evaporation, further exacerbating drought stress (Ding et al., 2021; Su et al., 2024; Wang et al., 2024). Conversely, in regions with high precipitation, the relatively abundant precipitation can meet the normal growth requirements of *P. orientalis* (Zhang et al., 2024); therefore, *P. orientalis*

in this region was rarely affected by drought stress during the growing season.

Comparing the growth resilience of *P. orientalis* along a precipitation gradient, the planted *P. orientalis* at the QLS site with medium precipitation showed significantly higher growth resilience after extreme droughts than that at the DWS site with low precipitation, indicating that increased precipitation will enhance the growth resilience of *P. orientalis* after extreme droughts (Wang et al., 2022; Che et al., 2023b). This finding also confirms the results of the climate–growth relationship (Fig. 3). Moreover, the growth resilience of *P. orientalis* after extreme droughts in 2016 and 2017 was significantly higher in the high-precipitation regions than in the medium-precipitation regions for two reasons. First, in this study, the SCZ site belongs to a natural *P. orientalis* forest. Through long-term evolution, the trees have adapted to and coped with extreme droughts. Therefore, under the same drought intensity, natural forests will exhibit stronger growth resilience after extreme droughts than plantation forests (Che et al., 2023a). Second, in the high-precipitation regions, abundant precipitation can meet the normal growth needs of *P. orientalis* (Fig. 3). When extreme droughts occur, precipitation can promptly replenish water. However, in the medium-precipitation regions, precipitation during tree growth period is insufficient to meet the water needs of trees, leading to a reduction in the synthesis of organics through photosynthesis. Consequently, the growth resilience of *P. orientalis* in the high-precipitation regions after extreme droughts was significantly higher than that in the medium-precipitation regions (Wang et al., 2022).

No extreme drought events were identified at the XJS site with low precipitation. This conclusion is based on the fact that the tree ring width series did not reach the threshold of growth decline compared to pre-drought, thereby reducing the frequency of extreme drought events. Moreover, this sampling site is located in the Xujiashan National Forest Park, where partial artificial irrigation occurs. Nevertheless, irrigation requires substantial human and material resources, and given the challenges of irrigation in semi-arid areas, future efforts should prioritize the effective utilization of precipitation to mitigate the impacts of extreme droughts and enhance the growth resilience of plantation forests after extreme droughts (Xiao et al., 2019; Yang et al., 2023; Che et al., 2024).

4.2 Guiding strategies for the management of *P. orientalis* plantation forests tailored to specific precipitation conditions

Specifically, at the DWS site with low precipitation, the "line of full resilience" and "line of actual resilience" did not exhibit a clear intersection point (Fig. 5a), suggesting that the plantation forests in this region may face difficulties in recover to their previous levels after extreme droughts. In other words, once extreme droughts affect the plantation forests with ongoing climate warming, the growth of *P. orientalis* may fail to keep pace with climate change, potentially leading to consecutive growth declines (Wang et al., 2022; Che et al., 2023b). Consequently, appropriate forest management measures should be implemented for *P. orientalis* plantation forests in this region at later stages, such as artificial irrigation at the XJS site, to maintain the stability of plantation forests in ecologically fragile areas and prevent degradation due to extreme droughts (Xiao et al., 2019; Zhang et al., 2024).

In the medium- and high-precipitation regions, the abscissa values of the intersection points of the two curves were 0.5223 and 0.6761, respectively, indicating that the possibility of full recovery of *P. orientalis* in the two regions was 47.77% and 32.39%, respectively. In other words, increased precipitation enhances the recovery ability of trees after extreme droughts (Schwarz et al., 2020; Wang et al., 2022; Che et al., 2023a). In addition, the possibility of full recovery of *P. orientalis* plantation forests in the medium-precipitation regions was slightly higher than that in the high-precipitation regions, possibly because of the data volume in this study. There were more extreme drought events associated with the medium-precipitation regions, leading to a more concentrated fit of the results. Figure 4 confirms that as precipitation increased, the growth resilience of *P. orientalis* was gradually enhanced, enabling the trees to recover. These findings also validate the hypothesis of this study that *P. orientalis* in regions with higher precipitation will exhibit greater recovery ability after extreme droughts than that in regions with less precipitation.

The mean sensitivity values of residual chronologies were relatively low at the artificially irrigated site of XJS in the low-precipitation regions compared to those in the medium-precipitation regions, indicating a high correlation between tree growth and environmental changes. This also suggests that plantation forests under the irrigated conditions exhibit less sensitivity to environmental changes and greater stability (Che et al., 2023a; Du et al., 2024). Therefore, for plantation forests in the medium-precipitation regions without artificial irrigation, measures to alleviate water scarcity can be implemented by altering land preparation, such as adopting rainwater harvesting and conservation practices through horizontal platforms and planting holes (Che et al., 2024; Su et al., 2024). Natural precipitation can meet the normal growth requirements of trees in the high-precipitation regions. Consequently, regular pruning and thinning can be employed post-management to prevent interspecific competition arising from excessive planting density (Loreau et al., 2001; Forrester, 2014; Li et al., 2021). In summary, different management strategies tailored to specific precipitation conditions and site characteristics should be adopted for *P. orientalis* plantation forests rather than implementing a "one-size-fits-all" approach to maintain the stability and sustainable development of plantation forests to the greatest possible extent.

5   Conclusions

In the context of climate warming, analyzing the growth resilience of plantation forests after extreme droughts along a precipitation gradient holds significant importance for regional forest ecological management. This study found that on the western Loess Plateau, precipitation played a key role in the growth resilience of plantation forests after extreme droughts. As precipitation increased, the growth resilience of planted *P. orientalis* after extreme droughts gradually enhanced, enabling it to recover to its pre-drought growth level. In the low-precipitation regions, the plantation forests had difficulty recovering to its pre-drought growth level, suggesting that conditional artificial irrigation can be applied to plantation forests in this area if possible. In the medium-precipitation regions, the growth of *P. orientalis* was significantly limited by drought stress; however, it possessed a certain degree of recovery ability after extreme droughts. In the high-precipitation regions, natural precipitation was sufficient for the growth of *P. orientalis*, and the impacts of extreme droughts on plantation forests were relatively weak. Our results provide valuable insights into plantation forest management on the western Loess Plateau and other similar vegetation restoration areas globally, emphasizing the need for targeted strategies tailored to local conditions under different precipitation conditions.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

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References

Allen C D, Macalady A K, Chenchouni H, et al. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management, 259(4): 660–684.

Beguería S, Vicente-Serrano S M, Reig F, et al. 2014. Standardized precipitation evapotranspiration index (SPEI) revisited: Parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. International Journal of Climatology. 34(10): 3001–3023.

Che C W, Xiao S C, Ding A J, et al. 2022. Growth response of plantations *Hippophae rhamnoides* Linn. on different slope aspects and natural *Caragana opulens* Kom. to climate and implications for plantations management. Ecological Indicators, 138: 108833, doi: 10.1016/j.ecolind.2022.108833.

Che C W, Xiao S C, Peng X M, et al. 2023a. Radial growth of Korshinsk peashrub and its response to drought in different sub-arid climate regions of northwest China. Journal of Environmental Management, 326(1): 116708, doi: 10.1016/j.jenvman.2022.116708.

Che C W, Xiao S C, Peng X M, et al. 2023b. Mixed of arbor-shrub significantly enhanced the drought stress adaptive capacity of plantation forests–An interpretation based on dendroecology. Journal of Hydrology, 623: 129785, doi: 10.1016/j.jhydrol.2023.129785.

Che C W, Zhang M J, Yang W M, et al. 2024. Dissimilarity in radial growth and response to drought of Korshinsk peashrub (*Caragana korshinskii* Kom.) under different management practices in the western Loess Plateau. Frontiers in Plant Science, 15: 1357472, doi: 10.3389/fpls.2024.1357472.

Dang H, Lü Y H, Wang X F, et al. 2025. Integrating species diversity, ecosystem services, climate and ecological stability helps to improve spatial representation of protected areas for quadruple win. Geography and Sustainability, 6(1): 100205, 10.1016/j.geosus.2024.06.005.

Ding A J, Xiao S C, Peng X M, et al. 2021. Shrub-rings used to reconstruct drought history of the central Alxa Desert, Northwest China. International Journal of Climatology, 41(10): 4957–4965.

Du D S, Jiao L, Wu X, et al. 2024. Drought determines the growth stability of different dominant conifer species in Central Asia. Global and Planetary Change, 234: 104370, doi: 10.1016/j.gloplacha.2024.104370.

Earles J M, Stevens J T, Sperling O, et al. 2018. Extreme mid-winter drought weakens tree hydraulic-carbohydrate systems and slows growth. New Phytologist, 219(1): 89–97.

Fang K Y, Guo Z T, Chen D L, et al. 2017. Drought variation of western Chinese Loess Plateau since 1568 and its linkages with droughts in western North America. Climate Dynamics, 49(11–12): 3839–3850.

Feng Y H, Schmid B, Loreau M, et al. 2022. Multispecies forest plantations outyield monocultures across a broad range of conditions. Science, 376(6595): 865–868.

Forrester D I. 2014. The spatial and temporal dynamics of species interactions in mixed-species forests: From pattern to process. Forest Ecology and Management, 312: 282–292.

Fu B J, Liu Y S, Cao Z, et al. 2023. Current conditions, issues, and suggestions for ecological protection and high-quality development in Loess Plateau. Bulletin of Chinese Academy of Science, 38(8): 1110–1117. (in Chinese)

Giana F E, Martínez-Meier A, Mastrandrea C A, et al. 2023. Intensity and number of thinning operations affect the response of *Eucalyptus grandis* to water availability and extreme drought events. Forest Ecology and Management, 529: 120635, doi: 10.1016/j.foreco.2022.120635.

Holmes R L. 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bulletin, 43: 69–78.

IPCC (Intergovernmental Panel on Climate Change). 2021. Climate change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press, 1800.

Jiang D B, Wang X X. 2021. A brief interpretation of drought change from IPCC Sixth Assessment Report. Transactions of Atmospheric Sciences, 44(5): 650–653. (in Chinese)

Jiang Y, Wang B Q, Dong M Y, et al. 2015. Response of daily stem radial growth of *Platycladus orientalis* to environmental factors in a semi-arid area of North China. Trees, 29(1): 87–96.

Jules E S, Jackson J I, van Mantgem P J, et al. 2016. The relative contributions of disease and insects in the decline of a long-lived tree: a stochastic demographic model of whitebark pine (*Pinus albicaulis*). Forest Ecology and Management, 381: 144–156.

Li C J, Fu B J, Wang S, et al. 2021. Drivers and impacts of changes in China's drylands. Nature Reviews Earth & Environment, 2: 858–873.

Li J T, Xie Y Y, Wulan T Y, et al. 2023. Drought resilience of Mongolian Scotch pine (*Pinus sylvestris* var. *mongolica*) at the southernmost edge of its natural distribution: A comparison of natural forests and plantations. Forest Ecology and Management, 542: 121104, doi: 10.1016/j.foreco.2023.121104.

Lloret F, Keeling E G, Sala A. 2011. Components of tree resilience: Effects of successive low-growth episodes in old ponderosa

pine forests. Oikos, 120(12): 1909–1920.

Loreau M, Naeem S, Inchausti P, et al. 2001. Biodiversity and ecosystem functioning: Current knowledge and future challenges. Science, 294(5543): 804–808.

Lu R, Zhang M J, Zhang Y, et al. 2024. Estimation of evapotranspiration from artificial forest in mountainous areas of western Loess Plateau based on HYDRUS-1D model. Journal of Arid Land, 16(12): 1664–1685.

Navarro-Cerrilloa R M, Manzanedo R D, Rodriguez-Vallejo C, et al. 2020. Competition modulates the response of growth to climate in pure and mixed *Abies pinsapo* subsp. *maroccana* forests in northern Morocco. Forest Ecology and Management, 459(1): 117847, doi: 10.1016/j.foreco.2019.117847.

Oggioni S D, Rossi L M W, Avanzi C, et al. 2024. Drought responses of Italian silver fir provenances in a climate change perspective. Dendrochronologia, 85(1): 126184, doi: 10.1016/j.dendro.2024.126184.

Schwarz J, Skiadaresis G, Kohler M, et al. 2020. Quantifying growth responses of trees to drought–a critique of commonly used resilience indices and recommendations for future studies. Current Forestry Reports, 6: 185–200.

Schweingruber F H, Eckstein D, Serre-bachet F. 1990. Identification, presentation and interpretation of event years and pointer years in dendrochronology. Dendrochronologia, 8: 9–38.

Su J R, Xiao S C, Peng X M, et al. 2024. Responses of radial growth to climate change for two dominant artificial coniferous trees. Dendrochronologia, 83(6): 126123, doi: 10.1016/j.dendro.2023.126163.

Sun B L, Ma L, Liu T X, et al. 2021. Changes in runoff in a typical temperate continental-monsoon transitional zone in the last four centuries. Journal of Hydrology, 596(36): 126124, doi: 10.1016/j.jhydrol.2021.126124.

Tian L, Zhang B Q, Chen S Y, et al. 2022. Large-scale afforestation enhances precipitation by intensifying the atmospheric water cycle over the Chinese Loess Plateau. Journal of Geophysical Research-Atmospheres. 127(16): e2022JD036738, doi: 10.1029/2022JD036738.

Vicente-Serrano S M, Beguería S, López-Moreno J I. 2010. A multi-scalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. Journal of Climate, 23(7): 1696–1718.

Wang B, Chen T, Li C J, et al. 2020. Radial growth of Qinghai spruce (*Picea crassifolia* Kom.) and its leading influencing climate factor varied along a moisture gradient. Forest Ecology and Management, 476: 118474, doi: 10.1016/j.foreco.2020.118474.

Wang B, Chen T, Li C J, et al. 2022. Discrepancy in growth resilience to drought among different stand-aged forests declines going from a semi-humid region to an arid region. Forest Ecology and Management, 511: 120135, doi: 10.1016/j.foreco.2022.120135.

Wang X F, Yang B, Ljungqvist F C. 2019. The vulnerability of Qilian juniper to extreme drought events. Frontiers in Plant Science, 10: 1191, doi: 10.3389/fpls.2019.01191.

Wang X F, Yang B. 2021. Divergent tree radial growth at alpine coniferous forest ecotone and corresponding responses to climate change in northwestern China. Ecological Indicators, 121: 107052, doi: 10.1016/j.ecolind.2020.107052.

Wang X G, Jiao L, Xue R H, et al. 2024. Radial growth in Qinghai spruce is most sensitive to severe drought in the Qilian Mountains of Northwest China. Journal of Forest Research, 35: 49, doi: 10.1007/s11676-024-01697-8.

Xiao S C, Peng X M, Tian Q Y, et al. 2019. Stem radial growth indicate the options of species, topography and stand management for artificial forests in the western Loess Plateau, China. Sciences in Cold and Arid Regions, 11(3): 226–238.

Xiao S C, Peng X M, Ding A J, et al. 2020. Research advance of shrub dendrochronology in the cold and arid regions of China. Advances in Earth Science, 35(6): 561–567. (in Chinese)

Yang L, Zhang Z H, Li Z S. 2019. Effects of large-scale re-vegetation on soil desiccation in the Loess Plateau: Problems and perspectives. Acta Ecologica Sinica, 39(20): 7382–7388. (in Chinese)

Yang Y, Zhang M J, Wang S J, et al. 2023. Soil moisture variability affected by sand mulch: An isotope-based assessment of irrigated farmland in Northwest China. Ecohydrology, 16(1): e2477, doi: 10.1002/eco.2477.

Zang C S, Buras A, Esquivel-Muelbert A, et al. 2020. Standardized drought indices in ecological research: Why one size does not fit all. Global Change Biology, 26(2): 322–324.

Zhang J Z, Gou X H, Zhang Y X, et al. 2016. Forward modeling analyses of Qilian Juniper (*Sabina przewalskii*) growth in response to climate factors in different regions of the Qilian Mountains, northwestern China. Trees, 30(1): 175–188.

Zhang Y, Zhang M J, Qiang Y Q, et al. 2024. Estimating non-productive water losses in irrigated *Platycladus orientalis* plantations in semi-arid mountainous: Based on stable isotopes. Science of the Total Environment, 934: 173279, doi: 10.1016/j.scitotenv.2024.173279.

Zhong Z Q, He B, Chen Y N, et al. 2021. Higher sensitivity of planted forests' productivity than natural forests to droughts in China. Journal of Geophysical Research-Biogeosciences, 126(10): e2021JG006306, doi: 10.1029/2021JG006306.

Appendix
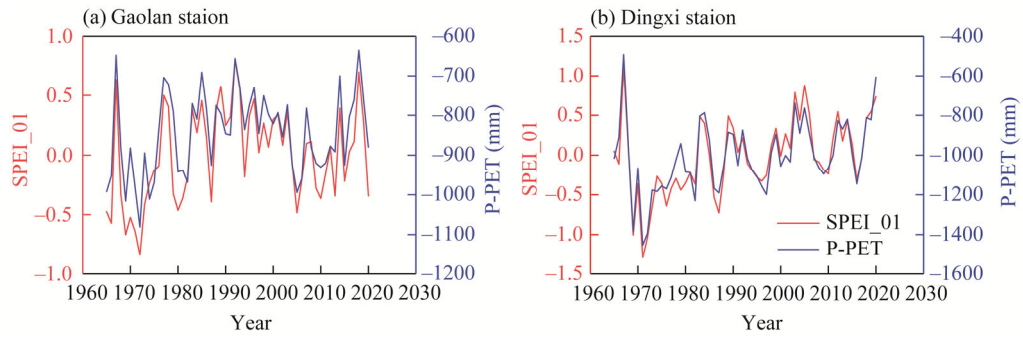
Fig. S1 Temporal variation in SPEI_01 and P-PET using meteorological data at Gaolan station (a) and Dingxi station (b). SPEI_01, standardized precipitation evapotranspiration index at the 1-month time scale. P-PET is the actual water shortage, defined as precipitation minus potential evapotranspiration.